COMPUTATIONAL LASER MICROMACHINING
FOR MACHINING PMMA

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Report submitted in partial fulfillment of the requirements for the award of the degree of
Bachelor of Mechanical Engineering with Manufacturing Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

DECEMBER 2010

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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ACKNOWLEDGEMENTS

I am grateful and would like to express my sincere gratitude to my supervisor Dr. Daw Thet Thet Mon for her germinal ideas, invaluable guidance, continuous encouragement and constant support in making this project possible. I appreciate her consistent support from the first day I applied to graduate program to these concluding moments. I am truly grateful for her progressive vision about my training in science, her tolerance of my naïve mistakes, and her commitment to my future career.

My sincere thanks go to all the members of the staff of the Faculty of Mechanical Engineering, UMP, who helped me in many ways by giving their fully co-operation and commitments. They made my stay at UMP pleasant and unforgettable. Many special thanks go to member laser research group for their excellent co-operation, inspirations and supports during this project.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I acknowledge the sincerity of my sisters who consistently encouraged me to carry on my degree. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. Special thanks should be given to my classmates. I would like to acknowledge their supports, comments and suggestions, which was crucial for the successful completion of this study.

ABSTRACT

Laser micromachining has many technological advantages compared to conventional technologies, including design flexibility, production of complex shape and possibility of rapid prototyping. Typical problems that may be faced with laser micromachining are laser-induced debris, large heat-affected zone and laser penetration depth. Frequently, high quality components are obtained by chance or at the expense of time and money due to inaccessible machining dimension, improper set of process parameter and large uncertainty in the process itself. To solve these problems, virtual laser micromachining with the aid of computational model is greatly desirable. This thesis presents a computational laser micromachining model for machining Polymethyl Methacrylate (PMMA). Laser micromachining parameters considered were laser power, spatial velocity and spot size. Finite element models were developed to simulate laser micromachining of PMMA. Time-dependent thermal analysis was used as analysis type. The geometry of the computational model is limited to two-dimensional (2-D) model and uniform mesh design is used. Material was modeled as isotropic and properties were obtained from literature. From result, the computational model was validated by comparing computed size of major cutting zone with experimental result. After validation, laser micromachining was simulated for varying laser parameters generated by design of experiment (DOE) in STATISTICA. These results will be analyzed in STATISTICA and the feasible process parameters were identified. Different parameter combinations provide different contour pattern and different size of major cutting zone. Laser power was found to be the most significant effect to the size of major cutting zone, followed by laser spot size and spatial velocity.

ABSTRAK

Laser mikro-mesin mempunyai banyak keunggulan teknologi berbanding dengan teknologi konvensional, termasuk fleksibiliti rekabentuk, pengeluaran bentuk yang kompleks dan kemungkinan prototyping cepat. Masalah khas yang mungkin dihadapi dengan laser mikro-mesin adalah laser-puing diinduksi, zon terkena panas yang besar dan kedalaman penetrasi laser. Sering, komponen berkualiti tinggi diperolehi secara kebetulan atau dengan mengorbankan masa dan wang kerana dimensi enjin tidak dapat dicapai, set parameter proses yang tidak tepat dan ketidaktentuan yang besar dalam proses itu sendiri. Untuk mengatasi masalah ini, laser mikro-mesin virtual dengan bantuan model pengkomputeran sangat dikehendaki. Tesis ini membentangkan model laser mikro-mesin pengkomputeran untuk mesin Polimetil Metakrilat (PMMA). Parameter laser mikro-mesin yang diambil kira adalah kuasa laser, kelajuan spasial dan saiz spot. Model Finite Elemen telah dibina untuk mensimulasikan laser mikro-mesin untuk PMMA. Analisis terma yang bergantung pada masa digunakan sebagai jenis analisis. Geometri dari model pengkomputeran terhad pada dua dimensi (2-D) model dan reka bentuk mesh seragam digunakan. Bahan dimodelkan sebagai isotropik dan cirri-ciri diperolehi daripada kesusasteraan. Dari keputusan, model pengkomputeran dikenal pastikan dengan membandingkan saiz zon pemotongan utama dengan keputusan eksperimen. Setelah pengesahan, laser mikro-mesin disimulasikan untuk parameter laser yang dihasilkan oleh rekabentuk eksperimen di Statistica. Keputusan ini akan dianalisa di Statistica dan parameter proses yang layak dikenalpasti. Kombinasi parameter yang berbeza memberikan pola kontur yang berbeza dan saiz zon pemotongan utama yang berbeza. Kuasa laser merupakan pengaruh yang paling signifikan terhadap saiz zon pemotongan utama, diikuti dengan saiz laser spot dan kelajuan spasial.

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LIST OF SYMBOLS

A	Area
c	Material specific heat
d	Spot size
d_0	Diameter of the beam at the focusing lens
d_{min}	Theoretical resolution
f	Focal length of the lens
h	Convection coefficient
k	Material thermal conductivity
ρ	Material density
P	Power
q	Heat flux
Q	Internal heat generation rate
s	The size of major cutting zone
T	Temperature of surface of the body
T_a	Ambient fluid temperature
U	Internal energy
V	Spatial velocity
λ	Wavelength of the laser

LIST OF ABBREVIATIONS

Ar	Argon
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CO_2	Carbon dioxide
DOE	Design of experiment
DP	Diode-pumped
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
HAZ	Heat affected zone
IR	Infra-Red
Kr	Krypton
Nd-YAG	Neodymium-Yttrium Aluminium Garnet
PMMA	Polymethyl Methacrylate
UV	Ultraviolet
Xe	Xenon
2-D	Two-dimensional
3-D	Three-dimensional

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Laser as it is known today has many applications especially in medical sector and in manufacturing sectors. Such application as welding and cutting, measuring or surveying a long distance, laser nuclear fusion, laser treatment and sensing are well-known to name a few (Agrawal and Dutta, 1986). More importantly laser had been used in micromachining since the last decade. The use of laser in micromachining has been a break-through technology since various types of laser were commercially available. Laser micromachining has many technological advantages compared to conventional technologies, including design flexibility, production of complex shape and possibility of rapid prototyping. Indeed, laser micro-fabrication had become one of the fast growing field of science and technology.

Laser micromachining is definitely a good alternative and unique way of processing materials which involve less thermal distortion and minimum metallurgical damage to work piece, compared to conventional methods such as photolithography, etching, LIGA, mechanical micromachining (Pryputniewicz, 2006). Laser involved in micromachining was only involving thermal effect of infrared laser beams to heat, melt and vaporize materials in the early stage. However, with the advance in technology, shorter wavelength ultraviolet (UV) and as well as ultrafast pulsing were discovered, a thermal mechanisms and interactions between beams material can be generated that are shorter than the mean free time between collisions in atoms and molecules. Moreover, micro machining with laser can also be very accurate and neglect the damage from thermal. Application in laser micromachining involve laser bonding of wafer, laser micromachining of three-dimensional (3-D) microchannel system in chemical, biomedical, DNA and environmental science (Pryputniewicz, 2006).

Typical problems that may be faced with laser micromachining are laser-induced debris, large heat affected zone (HAZ) and laser penetration depth. Frequently, high quality components are obtained by chance or at the expense of time and money due to inaccessible machining dimension, improper set of process parameter and large uncertainty in the process itself. To tackle these problems, virtual laser micromachining with the aid of computational model is greatly desirable. Furthermore, now with the development of advanced virtual technology and CAD/CAM/CAE system many realistic designs, analysis and simulations can be done on the computer prior to actual manufacturing.

As for Polymethyl Methacrylate (PMMA), it is a clear plastic, used as a shatterproof replacement for glass. The use of PMMA as the substrate material has several advantages and of it is that PMMA can prevent the contamination caused by biomolecule adsorption since it's a non-porous solid (Cheng et al., 2004). High clarity in combination with UV-resistance, modest impact strength, and abrasion-resistance make them useful especially in microstructure application such as micro nozzle and micro channels.

In this project, laser micromachining of various parameter combinations were carried out in finite element environment. In order to do so, novel computational models were developed using finite element modeling technique as this technique has been matured enough to develop reliable models (Michael, 2006). The models will help to determine the appropriate process parameters that would produce the high quality surface finish.

1.2 PROBLEM STATEMENT

The problem statements of this project are:

i. Detail experimental study of laser micromachining is expensive.
ii. Feasible laser micromachining parameter for PMMA is not well-known.

1.3 PROJECT OBJECTIVES

The objectives of this project are:

i. To develop a computational model that can simulate laser micromachining of PMMA.
ii. To validate the computational model with experimental result.
iii. To predict the parameter combinations during laser micromachining.

1.4 PROJECT SCOPES

The scopes of this project are:

i. The finite element code ALGOR will be used to develop computational model.
ii. The geometry of the computational model is limited to two-dimensional model.
iii. Isotropic material model will be used for a laser micromachining analysis.
iv. Simulation of laser micromachining will be carried out for various laser power, spatial velocity and spot size using computational model.
v. The computational result will be verified with experimental laser micromachining result done by others.
vi. Laser source used is Neodymium-Yttrium Aluminium Garnet (Nd-YAG) pulse laser.

1.5 OVERVIEW OF THE THESIS

This thesis consists of five chapters. Chapter 1, which is the introduction, states the project background, problem statement, project objectives and project scopes. Chapter 2 is the literature review where study is made on related studies from the previous researchers. Chapter 3 is the methodology of this project that describes the method, procedure and approach that had been used. Chapter 4 is the results and discussion of this project while chapter 5 is the conclusion and recommendation that had been made according to this project.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The main purpose of this chapter is to collect all the information related to this project with references from various sources such as books, journals, thesis and internet. A review of the literature was performed to identify studies that relevant to this project.

2.2 LASER MICROMACHINING

Laser micromachining is a direct machining method and is based on the interaction of laser light with solid matter. It uses intense ultraviolet (UV) or infrared radiation that provided by a laser to remove the polymer material. The removal mechanism is affected by the radiation wavelength used. Ultraviolet lasers in wavelengths of 157 to 351 nm are mostly used on polymers. If infrared lasers are used, the irradiated material is heated and decomposes, leaving a void in the polymer material. If UV radiation is used, the irradiated polymer decomposes, presumably by a mixture of two mechanisms: thermal and direct bond breaking, Thermal bond breaking is induced by heat, as with infrared radiation. In direct bond breaking, polymer molecules directly absorb ultraviolet photons, often absorbing enough energy so that the chemical bonds within the polymer chains are broken. The resulting smaller polymer chains are volatile or melt at much lower temperatures than the bulk polymers, thereby leaving a void in the material (Geschke et al., 2004).

Laser micromachining includes a wide range of processes where material is removed accurately but the term is also used to describe processes such as microjoining and microadjustment by laser beam. Most applications are found in the electronics industry in high-volume production. Lasers used for micromachining are characterized by short pulse lengths from the millisecond range for applications like mocrowelding to the pico- and even femtosecond area for ablation of metals (McGeough, 2002).

2.3 POLYMETHYL METHACRYLATE

In this project, Polymethyl Methacrylate (PMMA) is selected as the material as it is widely used recently. Figure 2.1 shows an example of PMMA.

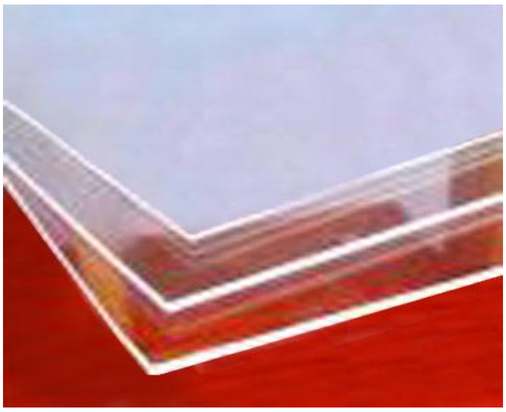

Figure 2.1: Polymethyl Methacrylate

PMMA is a versatile thermoplastic that is well suited for engineering and many common applications. PMMA is usually referred to as its commercial name which is acrylic. PMMA is used frequently in laser machining research as a material to prove the concept due to its low melting temperature, low sensible and latent heat and evaporation nature in phase change. Besides, it is one of the most suitable thermoplastic polymers for machining due to its thermal stability, chemical resistances, and low cost (ETHZ, 2006). PMMA also finds a wide range of applications in automotive, medical, industrial and consumer areas because of its excellent optical property and good weatherability, which is defined as the resistance to the detrimental effects under exposure to the environment.

Unmodified PMMA is almost completely transparent as glass and is utilized as a substitute for glass due to its inexpensive, nonpoisonous, weatherproof, lightweight, burns without residue and unbreakable nature. These favorable properties make it interesting for many uses. Typical automotive applications for PMMA include signal light devices for traffic, nameplates, display panels and glazing. Industrial applications for PMMA include display shelving, signs, instrument panel covers, lenses and skylighting (Liu, 1996).

The effects of CO_2 cutting parameters on the resulting cut quality for polymers were investigated by several researchers. Caiazzo et al. (2005) presented the application of the CO_2 laser cutting process to three thermoplastic polymers in different thicknesses ranging from 2 to 10 mm. They examined laser power, cutting speed, gas pressure, and thickness as cutting parameters. Davim et al. (2008) investigated cutting quality of PMMA by using CO_2 lasers. They presented some surface quality aspects of CO_2 laser cutting of linear and complex 2D. The effect of the process parameters (laser power and cutting velocity) on the quality of the cut for several polymeric materials was also investigated by Davim et al. (2008).

2.4 LASER TYPES

There are different types of lasers. Lasers can be divided into groups according to the different criteria:

i. The state of matter of the active medium: solid, liquid, gas, or plasma.
ii. The spectral range of the laser wavelength: visible spectrum, Infra-Red (IR) spectrum, etc.
iii. The excitation (pumping) method of the active medium: Optic pumping, electric pumping, etc.
iv. The characteristics of the radiation emitted from the laser.
v. The number of energy levels which participate in the lasing process.

These lasers are described as follows:

2.4.1 Gas lasers

Gas lasers can be categorized into the following three sub-groups according to the composition of the lasing medium: neutral atom, ion and molecular. For neutral atom laser, the active medium in these lasers is a noble gas in its neutral state, or a metal power. The helium–neon laser is a typical neutral atom laser and is used widely for applications of measurement, holography, alignment and vision. The laser active medium for ion gas lasers is composed of ionized gas. Ion gas lasers such as argon (Ar), krypton (Kr), and xenon (Xe) are used in applications such as surgery and spectroscopy. Molecular gas laser is where the laser active medium is composed of gas molecules. The most commonly used molecular laser is the carbon dioxide (CO_2) laser although carbon monoxide laser is also being used. A far infrared electromagnetic radiation with 10.6µm wavelength is emitted from a carbon dioxide laser. The lasing medium is a combination of the gases carbon dioxide, helium and nitrogen with the mixture ratio of roughly 5 %, 80 % and 15 % (Liu, 1996).

In particular, carbon dioxide laser ablation is considered as the most attractive and effective method for the polymer-based microfluidic device fabrication due to its inexpensive price and flexibility. Klank et al. (2002) first reported the CO_2 laser micromachining and back-end processing for the rapid production of PMMA based microfluidic systems. Furthermore, Jensen et al. (2003) used a CO_2 laser to produce cavities and microstructures in PMMA by moving the laser beam over the PMMA surface in a raster pattern. Huang et al. (2009) carried out their experiment using a commercially available CO_2 laser machine (F1-50W, HM Laser Machinery Co., LTD., China) which has a wavelength of 10.6 mm and a maximum output power of 50 W in the continuous-wave operation mode to cut the PMMA sheets.

2.4.2 Solid state lasers

The active medium in solid state lasers is a crystal or glass. Solid state lasers use ions in a crystalline matrix to produce laser light. The ions provide the electrons for excitation and the crystalline matrix propagates the energy between ions. Solid state lasers emit radiation in either pulsed mode or in continuous mode. Neodymium-Yttrium

Aluminium Garnet (Nd-YAG) laser is by far the most commonly used solid-state laser. Figure 2.2 shows diode-pumped continuous wave (CW) Nd-YAG laser.

Figure 2.2: Diode-pumped CW Nd-YAG laser

Nd-YAG lasers has laser output in the near infrared region with 1.06 µm wavelength. Although the YAG crystal has a relatively high thermal conductivity, continuous wave operation is limited to cutting since the achievable power is not very high due to the cooling problem of the heated YAG crystal. Nd-YAG lasers are generally used in the pulsed operation for scribing and marking due to the achievable high power and high pulsing rates. Solid state lasers use krypton, xenon, or semi-conductor laser diodes for optical pumping. Krypton flash lamps are useful for continuous wave operation while xenon flash lamps are used for pulsed mode operation since they can support the high current density required in pulsing. (Liu, 1996) The others solid state lasers include Ruby Laser, Neodymium (Nd) laser, Alexandrite Laser, Color Center Laser and Titanium Sapphire Laser (Arieli, undated).

In this project, laser micromachining of PMMA sheet is done by using Nd-YAG laser. Experimental results published in literature show that the Nd:YAG laser has some unique characteristics. Although the mean beam power is relatively low, the beam intensity can be relatively high due to smaller pulse duration and better focusing behaviour. Smaller kerf width, micro-size holes, narrower heat affected zone (HAZ) and better cut edge kerf profile can be obtained in Nd:YAG laser beam machining. Due to shorter wavelength, Nd:YAG laser is highly absorbed when falling even on a reflective surface (Dubey and Yadava, 2008).

The enhanced transmission through plasma, wider choice of optical materials and flexibility in handling with the advent of fibre optic beam delivery are also interesting characteristics of the Nd:YAG laser (Norikazu et al., 1996). Thick materials can be cut in pulsed mode operation which offers high peak power. The development of short pulse lasers using diode-pumped (DP) and Q-switching techniques (for frequency doubling and tripling) enables Nd:YAG lasers to be very useful tool in the field of micromachining (Meijer, 2004). In recent years, pulsed Nd:YAG lasers are being applied for precision cutting of thin sheets with narrow kerf, micro-drilling of holes and intricate profile cut.

2.4.3 Liquid lasers

Liquid lasers are mainly dye lasers using large organic dye molecules as the lasing medium. These dyes are capable of absorbing radiation from a wide range of frequencies in the spectrum from which the lasing can occur. The lasers are tunable in the sense that they can lase in the visible spectrum and parts of the infrared and ultra-violet spectra. Therefore, they are desirable for spectroscopic and photochemical applications (Liu, 1996).

Table 2.1 is listed common lasers with their wavelengths.

Table 2.1: Common lasers and their wavelengths

Laser type	Wavelength (nanometers)
Argon Fluoride	193
Xenon Chloride	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650

Source: Aldrich (undated)